Journal of Water Resource and Protection, 2020, 12, 316-329
https://www.scirp.org/journal/jwarp
ISSN Online: 1945-3108
ISSN Print: 1945-3094

Optimization of Irrigation Water Allocation Framework Based on Genetic Algorithm Approach

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How to cite this paper: Adama, G.J., Jimoh, D.O. and Otache, M.Y. (2020) Optimization of Irrigation Water Allocation Framework Based on Genetic Algorithm Approach. *Journal of Water Resource and Protection*, **12**, 316-329.
https://doi.org/10.4236/jwarp.2020.124019

Received: March 14, 2020
Accepted: April 18, 2020
Published: April 21, 2020

Abstract

In a world where excessive use and degradation of water resources are threatening the sustainability of livelihoods dependent on water and agriculture, increased food production will have to be done in the face of a changing climate and climate variability. There is a need to make optimal use of the available water resource to maximize productivity. Climate-smart irrigation is aimed at increasing per unit production and income from irrigated cropping systems without having negative impacts on the environment or other water users and uses. This paper developed a water allocation model using Genetic Algorithm to equitably allocation available water to the various sectors in Kano River Irrigation Scheme yielding an optimal as well as equitable water release with a 96.44% demand met. An average relative supply of 0.94 was obtained indicating the there was even supply of water to all the sectors. The model is robust and relatively easy to apply and can be employed by farm managers to achieve equity and optimal use of the available water resource.

Keywords

Climate-Smart Agriculture, Irrigation, Water Allocation, Sectors, Relative Water Supply

1. Introduction

Global water resources are under increasing pressure due to large-scale water abstraction for human needs [1] [2]. Agriculture is both a cause and victim of water scarcity, as the excessive use and degradation of water resources are threatening the sustainability of livelihoods dependent on water and agriculture [3]. Water scarcity is said to occur when demand for freshwater exceeds supply in a specified domain and of all sectors of the economy; agriculture is the most sensitive to water scarcity. Although the agricultural sector is sometimes viewed as a "residual" user of water, after domestic and industrial sectors, it accounts for 70 percent of global freshwater withdrawals, more than 90 percent of consumptive use [4]. About 70% of this water abstracted from freshwater systems is used for irrigation [5], yet, irrigation systems are under pressure to produce more food with lower supplies of water [6]. Although farmers have long adapted to environmental conditions, the severity of the predicted climate changes may be beyond many farmers' current ability to adapt and improve their agricultural production systems and livelihoods [7]; increased food production will have to be done in the face of a changing climate and climate variability [8]. The vulnerability of agriculture is increasing with the passage of time as climate change is badly affecting agriculture due to uncertainty in the availability and quality of natural resources [9]. However, there is an increasing interest focused on ensuring that both agriculture and irrigation become climate smart as a driven factor to ensure food security, improve rural livelihoods, and alleviate environmental risks for small-scale farmers [10].

Climate-smart agriculture (CSA) is the agriculture that sustainably increases productivity, enhances resilience, reduces or removes greenhouse gases where possible and enhances achievement of national food security [11]. The CSA has three concurrent objectives: 1) sustainably increasing farm productivity and income, 2) increasing adaptive capacity to climate change, and 3) reducing greenhouse gas emissions [12]. Climate-smart irrigation (CSI) is an important integral component of climate-smart agriculture. It is an irrigation approach for a given agro-climatic and societal context that may result directly or indirectly from the different aspects of climate change; it aims to increase per unit production and income from irrigated cropping systems without having negative impacts on the environment or other water users and uses (in space and time).

The performance of agricultural use of irrigation water in sub-Sahara Africa, as compared to Asia, has been characterized by inefficiency and poor management [13]. According FAO (2018) Sub-Saharan Africa (SSA) has the most significant potential for expanding irrigated agriculture in the world. But only one-fifth of the potential irrigable area has been developed despite its enormous land and water resources [14], of which the vast majority of this irrigated land is concentrated in just four countries: Madagascar, Nigeria, South Africa, and Sudan [15].

Irrigation practice in Nigeria has not achieved the set goals despite the huge investment involved. The available resources for agricultural and irrigation development are still underutilized including land, water resources, and other agricultural inputs [16]. Currently, the total arable land in the country is estimated at about 34.6 million ha; however, only 40% is under cultivation out of which less than 5% is irrigated [17] [18]. Notwithstanding the abundant land and water resources, the availability of land for crop production is under threat due to recently increased conflict of the resource among the farmers and the herders in some selected agro ecological zones of the country [19]. Although Nigeria irrigation system has recently started receiving due attention and there is an observed facelift in its development, there are still underline challenges that need to be adequately addressed such as inconsistent and unstable policies and inappropriate legal framework, funding constraint and farmers attitudes and awareness towards irrigation systems of crop production and lack of the farmers interested in the operation and maintenance of the large-scale irrigation facilities. [20] reported that poor knowledge of irrigation techniques among the farmers is one of the factors affecting their participation in large-scale irrigation scheme. Those that manage to participate are not equipped with the requisite knowledge for the operations and maintenance of the facilities. This problem is one of the current challenges being faced by the large-scale irrigation scheme in Nigeria. The participating farmers see the facilities as government properties which should be maintained by the government. These do not only make the equipment short-lived but has also resulted in the abandonment of irrigation scheme due to lack of irrigation equipment and infrastructure to make use of. Furthermore, in irrigation scheme like the Hadeja-Jama' are river project, the utilization of the project is just about 50% while the Zobe dam in Dutsin-Main Katsina, which was constructed 40 years ago, currently has very little irrigation activities. Also, at the Bakolori irrigation dam in Zamfara State, under the Sokoto Rima Water Project, the area cultivated is not commensurate with the amount of water in the dam [21].

Kano River Irrigation Project (KRIP) being one of the first, largest and said to be the best performing irrigation project in Nigeria, has been in existence for over four decades and has not met up to ten percent of the design capacity. The dominant problems as identified by [14] range from water distribution, water management, waterlogging, salinity, sodicity, reduced fertility, obliteration of the irrigation and drainage infrastructure. This paper is focused on addressing water management issues by developing an irrigation water allocation model that will ensure equity in water, ensure the proper management and distribution of water to the users.

2. Materials and Method

2.1. The Study Area

The study area is located in the Kano State of Nigeria in Kano State between latitudes 11˚30'N and 12˚03'N and longitudes 8˚30'N and 9˚40'E. Kano River Irrigation Project, Phase I (KRIP I) is part of the Kano River Project which began in 1965 as a pilot project. It covers potentially irrigable land of 22,000 ha, which forms the study area. To this end, the area developed for irrigation is 16,500 ha while the area cropped ranges between 13,900 ha for dry season and 16,450 ha in wet seasons. KRIP I is a unique design, in that, the entire water distribution network operates on gravity owing to the elevation of 440 meters above sea level, with a minimum of the supply dam at 506.50 meters [14].

Tiga Dam is the source of irrigation water to the project site through the Ruwan Kanya Reservoir and the 18 km long main canal II, which splits into West and East branch canals. These are then distributed to all sectors, to sector turnouts, to distributor canals, to field canals and siphoned to blocks or farmlands. The excess is designed to be collected from the end of the field through field drains to collector drains and to main drains and back to the Kano River. The land is cultivated throughout the year (dry and wet season). Rainfall annual mean varies from about 884 mm to 600 mm in the north to 1200 mm in the south. Rain is more in five months (May-September) with August, recording the highest amount and mean annual temperature ranges from 26˚C - 33˚C. The yearly rainfall amount in Kano is increasing, especially in July and August [22]. Rice, Maize, Wheat, Onions and, Tomato are the main crops along with Sorghum, Vegetables, Cowpea, and Millet [14].

2.2. Data Collection

1) Primary Data for KRIP include: Number of sectors, irrigation network, irrigable land, Antecedent cropping pattern.

2) Secondary Data (NIMET and HJRBRDA): Monthly rainfall, temperature (maximum and minimum), relative humidity, sunshine hours, wind speed from (1980-2010) a period of 30 years [23].

2.3. Methodology

2.3.1. Determination of Monthly Evapotranspiration Using the Penman Monteith Evapotranspiration Model

Evapotranspiration (ET_o) is the combination of evaporation and transpiration of hydrological cycle. Both evaporation and transpiration shows the effect on hydrological cycle. Therefore, it plays a major role in the planning and management of water resources system, irrigation system design and hydrologic and drainage studies [24].

The monthly evapotranspiration of Kano River irrigation project was determined by employing FAO Penman-Monteith equation as shown in Equation (1):

$$ET_o = \frac{0.408\Delta\left(R_n - G\right) + \gamma\left(\frac{900}{T_{\text{mean}} + 273}\right)U_2\left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34U_2\right)} \tag{1}$$

where ET_o is reference evapotranspiration (mm·day^{-1}), R_n net radiation at the crop surface (MJ·m^{-2}·day^{-1}), G soil heat flux density (MJ·m^{-2}·day^{-1}), T mean daily air temperature at 2 m height (˚C), U_2 wind speed at 2 m height (m·s^{-1}), e_s saturation vapour pressure (kPa), e_a: actual vapour pressure (kPa), $e_s - e_a$: saturation vapour pressure deficit (kPa), Δ slope vapour pressure curve (kPa·˚C^{-1}), while γ psychrometric constant ((kPa·˚C^{-1}). Penman-Monteith method has been recommended by the United Nations Food and Agriculture Organization (FAO) as the single method for estimating reference evapotranspiration throughout the world. The FAO-56 based on the Penman-Monteith (Allen *et al.* 1998) method is considered to be a standard method [25].

2.3.2. Determination of Crop Water Need (ET_{crop})

Steps for determining crop evapotranspiration, ET_{crop}:

1) Identifying the crop growth stages, determining their lengths, and selecting the corresponding K_c coefficients;

2) Adjusting the selected K_c coefficients for frequency of wetting or climatic conditions during the stage;

3) Constructing the crop coefficient curve (allowing one to determine K_c values for any period during the growing period); and

4) Calculating ET_{crop} as the product of ET_o and K_c.

The general lengths for the four distinct growth stages and the total growing period for various types of climates and locations were employed as provided by FAO Irrigation and Drainage Paper No. 24 [26]. Crop water need was calculated based on the monthly reference crop evapotranspiration and the crop factor for each crop as shown in Equation (2) below based on FAO 56 standard.

$$ET_{\text{crop}} = ET_o \times K_c \tag{2}$$

where ET_{crop} is crop water need and K_c the crop factor. Crop factor varies for crops at various growth stages which include; initial, crop development, mid and late stages of growth.

2.3.3. Determination of Crop Water Requirement (CWR)

Crop water requirement is the amount of water required to compensate the evapotranspiration loss from the cropped field. Crop water requirement for the various sectors on weekly bases were computed for the crop water needs and the area of each sector as shown in Equation (3)

$$\text{CWR} = ET_{\text{crop}} \times A \tag{3}$$

where CWR is the crop water requirement, ET_{crop} is crop water need and A is the area of each sector.

2.3.4. Determination of Relative Water Supply (RWS)

The relative water supply is the ratio of supply water to demand. The relative water supply of the irrigation scheme is in Equation (4).

$$\text{Relative water supply}\left(\text{RWS}\right) = \frac{\text{volume of water allocated}}{\text{crop water requirement}} \tag{4}$$

2.4. Model Formulation

A number of alternative objective function formulations are possible for the water allocation problem. The most appropriate function has been found to be of the form [27]:

$$\text{Minimize } z = \sum_{i=1}^{n} \frac{\left(d_i - x_i\right)^2}{d_i} \tag{5}$$

where n is the number of irrigation schemes, d_i the irrigation demand for scheme i and x_i the irrigation supply to scheme i. The Genetic Algorithm flow chart for the water allocation is shown in Figure 1. The above equation is subject to canal capacity constraints, and supply constraints defined mathematically as:

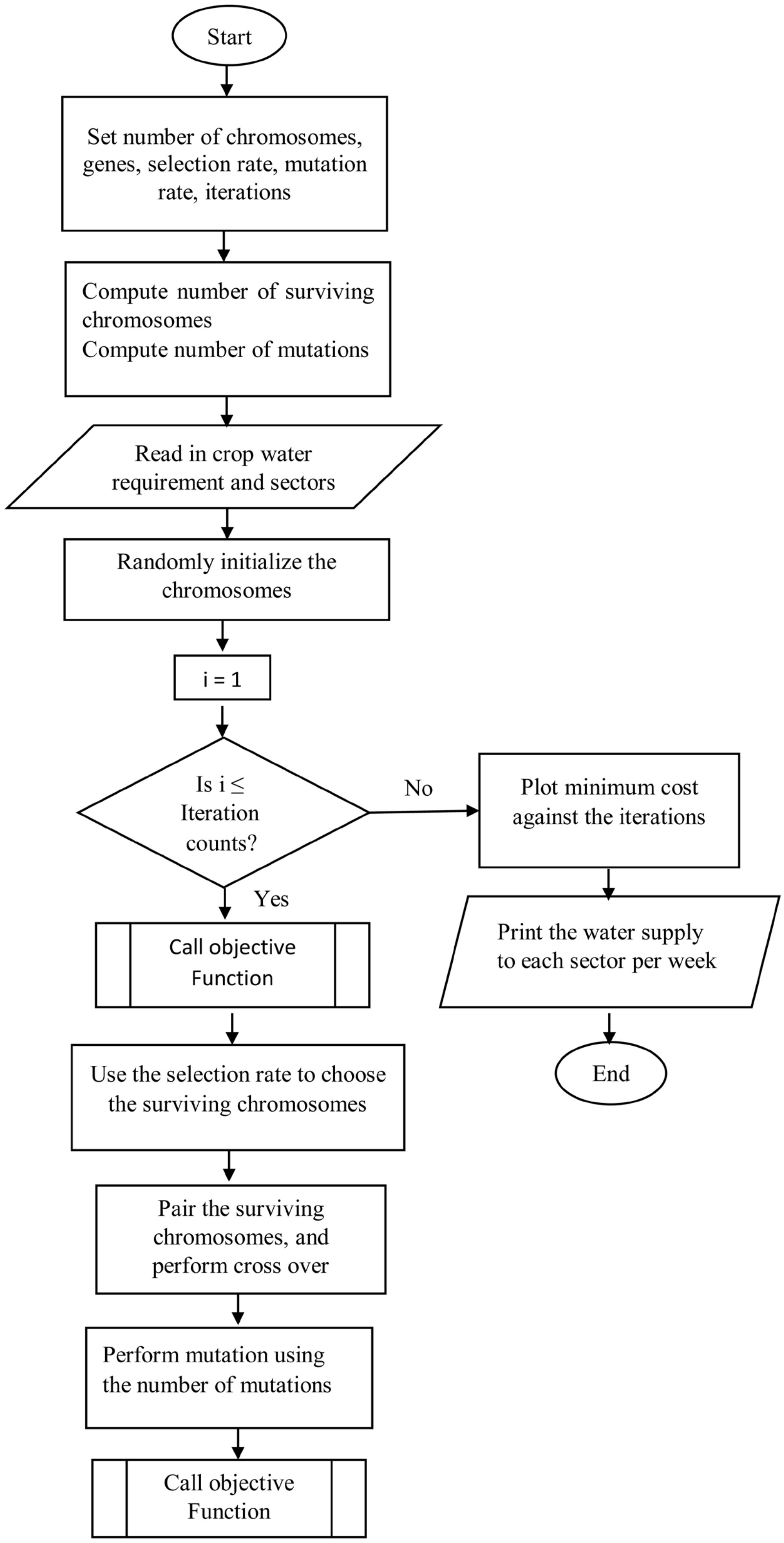


Figure 1. Flow chart for water allocation model.

$$x_{i,w} \le d_i$$

$$\frac{x_{i,w}}{d_{i,w}} \le 1.0$$

Equation (5) was rearranged to Equation (6)

$$\text{Minimize } z = \frac{\left(\sum_{i=1}^{52}\sum_{j}^{38}\text{supply}_{i,j} - \min\left(\sum_{i=1}^{52}\sum_{j}^{38}\text{demand}_{i,j}, Q\right)\right)^2}{\min\left(\sum_{wk=1}^{52}\sum_{j}^{38}\text{demand}_{i,j}, Q\right)} \tag{6}$$

where i is the number of weeks, j is the number of sectors and Q is the weekly available water, subject to the constraint which states that the allocated supply to each sector should not exceed the minimum of either the weekly demand of each sector or the total weekly available supply was evaluated accordingly as in Equation (7).

$$\text{supply}_{wk,sector} \le \min\left(\text{demand}_{wk,sector}, Q\right) \tag{7}$$

The water allocation model was developed by employing Genetic algorithm (GA) optimization technique. The model was optimized by using Genetic Algorithm (GA) as in MATLAB® 2013a. The objective function which minimizes the water allocated for the i^{th} number of weeks to the j^{th} number sectors is as shown in Equation (4). The flow chart for the objective function is shown in **Figure 2**.

3. Results and Discussion

The result of the reference evapotranspiration of Kano computed using the Penman-Monteith method is shown in **Table 1**. The average monthly reference evapotranspiration ranges from 4.33 mm/day in August to 7.39 mm/day in April. This is partly accordance with the findings of [28], observed that evapotranspiration for Kano is very low in rainy season having lowest value in August and high during dry season with its highest value in February, although in the case of the study, the evapotranspiration was highest in April.

The crop water need (ET_{crop}) was computed for each crop from Equation (2). The crops were planted at various weeks based on FAO 56 standard. The irrigation duration was for 36 weeks, when planting started in week 40 through week 23 of the next year.

Other details of the crops are presented in **Table 2**. It was observed that rice had the highest crop water need of 1124.71 mm although rice did not have the longest growth duration while maize had the lowest crop water need of 520.33 mm although maize did not have the longest growth duration. The crop water need is largely dependent on the crop factor of the crops at the different growth stages that the growth duration of the crops.

The crop water requirement for the entire irrigation scheme was then computed based on the crop water need based and cropping pattern of the Kano River Irrigation Project. The result of the crop water requirement is shown in **Table 3**.

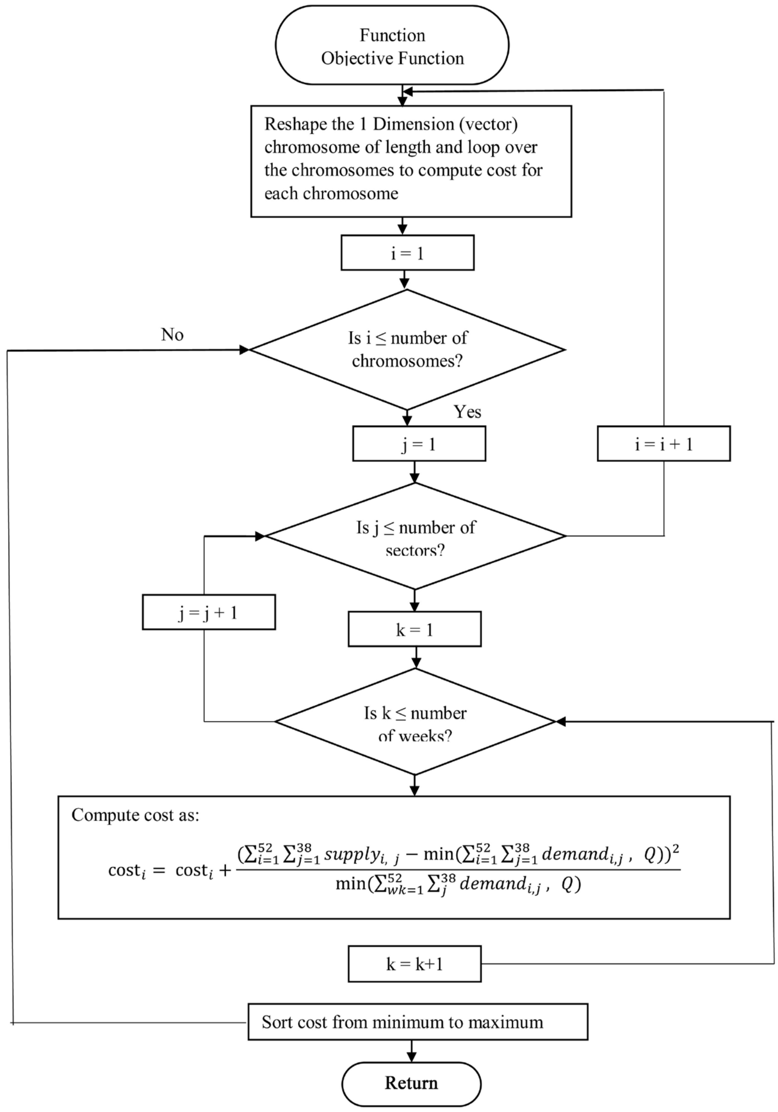


Figure 2. Flow chart of objective function for water allocation.

Table 1. Trend of Evapotranspiration (ETo) of KRIP.

Month	ETo (mm/day)
January	5.52
February	6.33
March	6.98
April	7.39
May	6.95
June	5.86
July	4.84
August	4.33
September	4.85
October	5.51
November	5.69
December	5.49

Table 2. Irrigation characteristics for respective crops.

Crop	Maize	Tomato	Wheat	Vegetable	Onion	Cowpea	Rice
Planting week	40	42	46	46	42	9	49
Harvest week	3	13	23	8	11	23	18
Total growth duration (weeks)	16	26	30	15	22	15	22
Total ET_{crop} during growth (mm)	520.33	968.77	1018.34	546.55	778.61	557.12	1124.71
Minimum ET_{crop} (mm/week)	15.43	17.36	13.94	17.92	19.29	17.1	42.27
Maximum ET_{crop} (mm/week)	44.44	56.19	59.49	44.34	41.82	53.52	63.52

Table 3. Crop water requirement of Kano River Irrigation Project in MCM.

Month	Weeks	CWR (MCM)	Month	Weeks	CWR (MCM)
October	Week 40	0.172	February	Week 6	4.028
	Week 41	0.172		Week 7	4.082
	Week 42	0.555		Week 8	4.082
	Week 43	0.793		Week 9	4.439
	Week 44	0.793	March	Week 10	4.931
November	Week 45	0.882		Week 11	4.964
	Week 46	1.053		Week 12	4.763
	Week 47	1.053		Week 13	4.771
	Week 48	1.668	April	Week 14	3.933
December	Week 49	3.580		Week 15	3.873
	Week 50	3.722		Week 16	3.042
	Week 51	3.722		Week 17	2.981
	Week 52	3.727		Week 18	2.481
January	Week 1	3.756	May	Week 19	0.496
	Week 2	3.783		Week 20	0.412
	Week 3	3.785		Week 21	0.277
	Week 4	3.237		Week 22	0.251
	Week 5	3.203	June	Week 23	0.250

The total crop water requirement for Kano River Irrigation Project was estimated to be 119.51 MCM with peak demand of 4.964 MCM obtained in week 11. At full canal capacity, the weekly available water is 5.184 MCM. The weekly demand and the optimized release during the entire group period are shown in Figure 3. It was observed that the optimized release was very close to the demand for all the weeks during the entire growth period, supplying just what is needed by the crops.

Table 4 shows the demand vs supply of all the 38 sectors in KRIP, it also shows the relative water supply of each sector. It was observed that the water allocated was closely matched with the demand (crop water requirement). Resulting to a 96.44% demand met. The GA Parameters used for the water allocation model are outlined in **Table 5**.

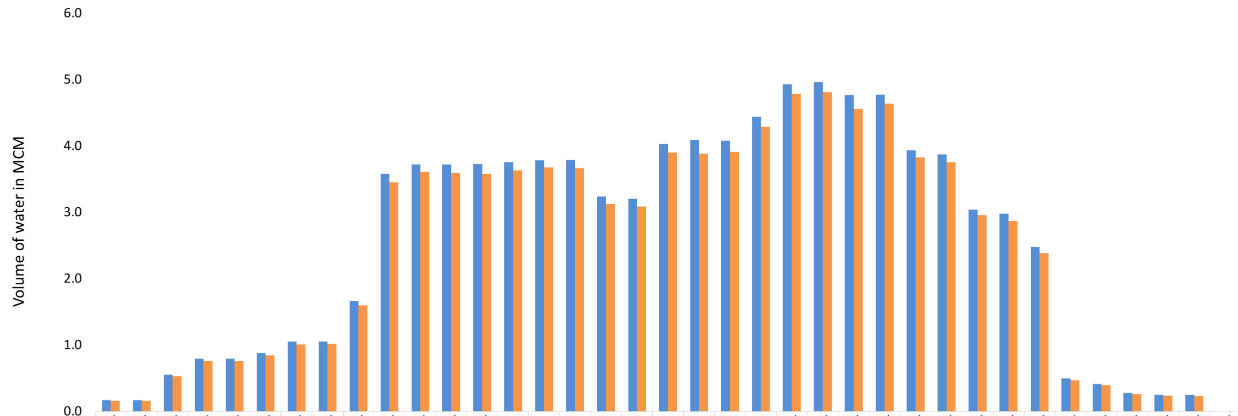
An overall optimized relative water supply of 0.96 was obtained for KRIP, with 0.94 and 0.99 as the minimum and maximum relative water supply respectively. The optimized relative water supply for Kadawa sector, Azore sector and Karfi sector where compared with those measured in the 90's in a study by [29]. **Figures 4-6** show the minimum and maximum relative water supply for the three sectors respectively.

Table 4. Demand vs supply in MCM of the sectors and their relative water supply.

	Sector	Demand	Supply	RWS		Sector	Demand	Supply	RWS
1	Waire	1.74	1.67	0.96	20	Pako	1.26	1.20	0.95
2	Bangaza	2.98	2.86	0.96	21	Butalawa	4.51	4.32	0.96
3	Yantomo	1.89	1.82	0.96	22	Majabo	1.50	1.44	0.96
4	Kadawa	1.11	1.05	0.95	23	Karfi	9.15	8.87	0.97
5	Gafan 1	0.12	0.11	0.95	24	Yakassai	3.60	3.45	0.96
6	Gafan 2	4.01	3.85	0.96	25	Kosawa	4.23	4.01	0.95
7	Agalawa	1.52	1.46	0.96	26	Gayere	1.26	1.20	0.95
8	Raje	1.21	1.14	0.94	27	Dorawa	3.83	3.67	0.96
9	Maura	2.78	2.67	0.96	28	Barnawa	0.64	0.61	0.95
10	Kore	17.57	17.35	0.99	29	Shiye	0.28	0.27	0.95
11	Azore	0.68	0.65	0.95	30	Chirin	1.74	1.68	0.97
12	Samawa	1.38	1.32	0.96	31	Kode	1.07	1.02	0.95
13	Gabas	1.19	1.13	0.94	32	Yuri	0.65	0.63	0.97
14	Tsauni	0.44	0.41	0.95	33	Kuruma	1.44	1.38	0.95
15	Rakauna	2.12	2.03	0.96	34	Turba	1.28	1.22	0.95
16	Gori South	0.89	0.85	0.96	35	Tsambaki	0.81	0.76	0.94
17	Gori North	1.47	1.43	0.97	36	Lautaye	3.42	3.29	0.96
18	Agolas	6.16	5.97	0.97	37	Bunkure	1.48	1.42	0.96
19	Balili	0.56	0.54	0.96	38	Korawa	1.71	1.63	0.95

Table 5. GA parameter for optimization of water allocation.

GA Parameter	Value
Population size	40
Number of Genes	1976
Selection rate	0.5
Generations	10,000
Mutation rate	0.2



	October					November				December				January				
	wk 40	wk 41	wk 42	wk 43	wk 44	wk 45	wk 46	wk 47	wk 48	wk 49	wk 50	wk 51	wk 52	wk 1	wk 2	wk 3	wk 4	wk 5
Demand (CWR)	0.2	0.2	0.6	0.8	0.8	0.9	1.1	1.1	1.7	3.6	3.7	3.7	3.7	3.8	3.8	3.8	3.2	3.2
Optimized Release	0.2	0.2	0.5	0.8	0.8	0.8	1.0	1.0	1.6	3.4	3.6	3.6	3.6	3.6	3.7	3.7	3.1	3.1

	February				March				April					May				June	
	wk 6	wk 7	wk 8	wk 9	wk 10	wk 11	wk 12	wk 13	wk 14	wk 15	wk 16	wk 17	wk 18	wk 19	wk 20	wk 21	wk 22	wk 23	wk 24
Demand (CWR)	4.0	4.1	4.1	4.4	4.9	5.0	4.8	4.8	3.9	3.9	3.0	3.0	2.5	0.5	0.4	0.3	0.3	0.2	0.0
Optimized Release	3.9	3.9	3.9	4.3	4.8	4.8	4.6	4.6	3.8	3.8	3.0	2.9	2.4	0.5	0.4	0.3	0.2	0.2	0.0

Figure 3. Demand vs optimized water release in Kano River Irrigation Project.

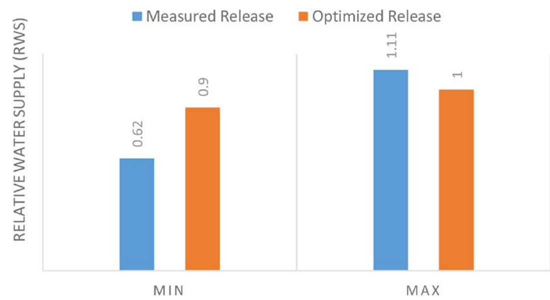


Figure 4. Optimized vs measured relative water supply of Kadawa sector.

Figure 5. Optimized vs measured relative water supply of Azore sector.

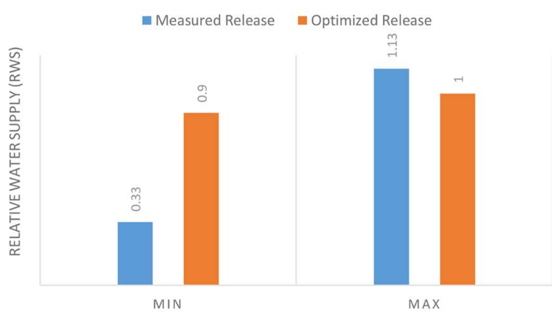


Figure 6. Optimized vs measured relative water supply of Karfi sector.

It was observed that the measured relative water supplies indicates uneven supply of water during the planting season and also tail end problem, while the optimized relative water supplies indicates fairly uniform relative water supplies during the planning season also eliminating tail end problem.

4. Conclusion

The optimisation approach developed to minimize the gap between supply and crop water requirement based on the Genetic Algorithm optimization technique is robust and relatively easy to apply. Applying it to a real-time irrigation scheme, it has proven to be an effective tool in decision making tool for effective water allocation as the water allocation model yielded an optimal as well as equitable water release with a 96.44% demand met. An average relative supply of 0.94 was obtained indicating that there was even supply of water to all the sectors. The model can be employed by farm managers to achieve equity and optimal use of the available water resource.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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